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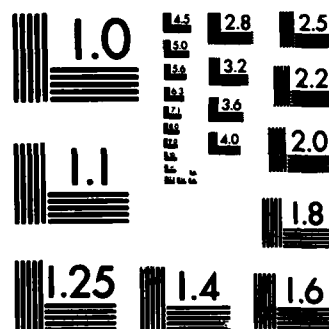
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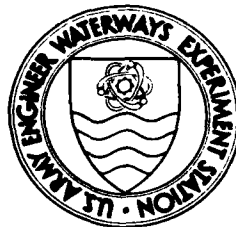
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SEISMIC DESIGN, ANALYSIS, AND REMEDIAL MEASURES TO IMPROVE STABILITY OF EXISTING EARTH DAMS

by

William F. Marcuson III and Arley G. Franklin

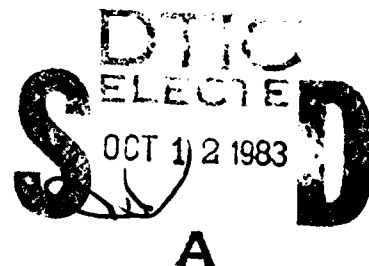
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Earthquake	Remedial treatment									
Earthquake engineering	Seismic design									
Foundations	Seismic stability									
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <p>→ This report discusses the seismic design of new embankment dams and analysis of existing dams, and possible courses of action to mitigate seismic hazards in the event that analysis indicates unsatisfactory conditions. Also discussed are the use of pseudostatic stability analysis and appropriate seismic coefficients.</p> <p>Several courses of action to deal with unsatisfactory conditions have</p> <p style="text-align: right;">(Continued)</p>										

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20. ABSTRACT (Continued).

been identified as being potentially feasible. These actions are designed either to reduce the risk of failure or to assure that the consequences will be tolerable should a damaging earthquake occur near an existing dam judged susceptible to earthquake-induced liquefaction. An essential condition is that the accomplishment and the effects of the proposed remedial work be verifiable. Courses of action discussed include (a) no action, (b) regulation of public access downstream, (c) partial lowering of the pool, (d) permanent emptying of the reservoir, (e) in situ densification of the foundation, (f) surcharge, (g) dewatering, (h) reduction in the drainage paths, (i) grouting, (j) construction of a replacement structure, (k) replacement in a new location, and (l) construction of a detention dam.

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Preface

This report was originally written as a paper for presentation at the 1983 Annual Meeting of the American Society of Civil Engineers at Philadelphia, Pa. The report was prepared by Drs. W. F. Marcuson III and Arley G. Franklin, respectively Chief, Geotechnical Laboratory (GL), and Chief, Earthquake Engineering and Geophysics Division, GL, U. S. Army Engineer Waterways Experiment Station (WES). Publication of this report was funded by the Office, Chief of Engineers (OCE), U. S. Army, under CWIS Work Unit 32219, which is monitored for OCE by Mr. Richard Davidson.

The authors wish to acknowledge the contributions of Dr. P. F. Hadala, Assistant Chief, GL, whose ideas on remedial measures have been freely used. Dr. Hadala and Mr. J. L. Von Thun, U. S. Bureau of Reclamation, Department of the Interior, technically reviewed this report.

The Commander and Director of WES during the period of this work was COL Tilford C. Creel, CE. The Technical Director was Mr. Fred R. Brown.



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SEISMIC DESIGN, ANALYSIS, AND REMEDIAL MEASURES TO IMPROVE
STABILITY OF EXISTING EARTH DAMS

Introduction

1. In recent years the public and the Government have become acutely aware of the need for improvement of dam safety in the United States as a result of several recent dam failures and near-failures. Examples of recent dam failures are the Walter F. Bouldin Dam in Alabama, the Toccoa Falls Dam in Georgia, the Buffalo Creek Dam in West Virginia, the Canyon Lake Dam in South Dakota, the Lawn Lake Dam in Colorado, the Teton Dam in Idaho, and the Baldwin Hills Dam in California. None of these failures was related to seismic activity, but on 9 February 1971, the San Fernando earthquake caused a massive slide in the upstream face of the Lower San Fernando Dam. This is not considered a dam failure because the reservoir did not escape in an uncontrolled manner. Had the dam failed, it might have resulted in the greatest single catastrophe in the history of the United States, since the earthquake occurred at about 6:00 a.m. and some 80,000 people resided immediately downstream. The narrowness of this escape is emphasized by the fact that if the reservoir had been at the same level that it was on the same day one year earlier, the dam would have been overtopped (Seed et al. 1973). These events have led to a national program for dam safety. Shortly before the near-failure of the Lower San Fernando Dam, the U. S. Army Corps of Engineers instituted a program to evaluate the seismic safety of all its dams, with particular emphasis on hydraulic-fill dams and dams founded on saturated sands.

2. During the past decade, the U. S. Army Engineer Waterways Experiment Station (WES) has gained extensive experience in the dynamic analysis of earth dams. This experience leads one to believe that the analysis of an existing dam is a considerably more difficult problem than the seismic design of a new dam. This is because in designing a new dam, geometry and materials can be specified to assure seismic safety, and marginal materials can always be removed or treated; while in analysis of existing dams there is the problem of discovering the reality of as-built conditions and there sometimes are marginally stable materials which lead to analytical results that are not clear-cut.

3. The purpose of this report is to discuss seismic design and analysis

of existing dams, and to discuss possible courses of action which can be taken to mitigate seismic risk in the event that the analysis indicates unsatisfactory conditions. The scope of this paper is limited to dynamic problems associated with earth dams. Problems associated with static or steady-state loading conditions will not be discussed. The statements made and positions taken in this paper, other than those contained in Engineer Regulation (ER) 1110-2-1806, are those of the authors and do not necessarily reflect official policy or positions of the Corps of Engineers.

Seismic Design of Earth Embankments

4. Formal criteria for seismic design of new Corps of Engineers dams are given in ER 1110-2-1806, dated 30 April 1977. This regulation reflects Corps of Engineers experience up to that date and a revised version that will reflect more recent experience and research is expected in the near future. This regulation provides criteria for seismic design, establishes requirements for geological and seismological investigations and engineering analysis, and discusses methods of dynamic analysis. It also provides guidance on the application of the results of analysis and the use of "defensive design" methods to provide protection against contingencies that are not amenable to analysis. Table 1 summarizes the essentials of the design criteria provided in ER 1110-2-1806. Design criteria are provided for an Operating Basis Earthquake (OBE), which is defined as the largest earthquake that is likely to occur during the life of the project, and for the Maximum Earthquake (ME), which is defined as the most severe earthquake that is possible at the site on the basis of geological and seismological evidence. In the case of the OBE, the criteria are calculated to limit economic losses and interference with the services and protections provided by the dam. Criteria for the ME are designed to assure public safety in the event of a major earthquake, but consider economic losses to the dams themselves to be tolerable in these extreme, rare events. The concept of the OBE was formulated for structures whose response within certain ranges can be considered elastic; it is not applied to embankment dams, which are designed on the basis of the ME.

5. Table 2 outlines the investigations and analyses that are required for new designs of Corps Dams, both concrete and embankment. For embankment dams, the regulation provides for the continued use of the seismic coefficient

Table 1

Design Criteria and Design Earthquakes

	<u>Operating Basis Earthquake (OBE)</u>	<u>Maximum Earthquake (ME)</u>
Embankment dams	--	Should be capable of retaining reservoir - deformation is acceptable
Concrete dams	Structure should perform essentially within elastic range, remain operational, and not require extensive repair	Should be capable of surviving without failure of a type that would result in loss of life or excessive property loss

Table 2

Investigations and Analyses Required

<u>Seismic Zone</u>	<u>Seismic Coefficient for Pseudostatic Analysis</u>	<u>Geological and Seismological Review (Locate Faults and Determine Seismic History)</u>	<u>Geological and Seismological Evaluation (Establish Design Earthquakes) and Dynamic Analysis</u>
0	0	All major dams	If capable faults or recent epicenters found within a distance where structural damage could be caused
1	0.025		
2	0.05		
3	0.10		As above, or if foundation liquefaction potential exists
4	0.15		All major dams

method in design and adds requirements for state-of-the-art dynamic analysis for critical structures in locations of high seismic activity or where a liquefaction potential exists. The term "major dam," as used in Table 2, is defined in terms of safety rather than size and/or cost; it refers to any dam that would endanger lives or cause serious property loss in the event of failure.

6. Table 2 also contains seismic coefficients for various seismic zones, as defined in ER 1110-2-1806, in the contiguous United States. If the embankment and foundation contain no materials that are subject to significant cyclic strength degradation, then pseudostatic stability analyses using appropriate seismic coefficients are adequate for predicting stability. The Corps of Engineers policy on seismic evaluation of existing dams or of dams presently under construction imposes requirements for investigations and analyses similar to those for new designs with the exception that new seismic coefficient analyses are not called for.

7. The authors' experience suggests that an appropriate seismic coefficient might be one-third to one-half the maximum acceleration to which the dam might be subjected. This acceleration value should include any amplification caused by the foundation or by the embankment. For example, if the design earthquake was assumed to have a maximum bedrock acceleration of 0.15 g and this motion is amplified through the foundation and embankment so that the maximum acceleration at the dam crest is 0.40 g, an appropriate seismic coefficient for a pseudostatic analysis might be 0.15. This analysis should use appropriate strength parameters and should yield a factor of safety greater than 1.0. In this case, one can expect limited deformations which would not threaten the integrity of the dam or the reservoir if the design earthquake occurs. These statements are based on the results of a large number of published (Franklin and Chang 1977 and Newmark 1965) and unpublished sliding block analyses, examination of which indicates that permanent displacements would be small if the yield acceleration exceeds one-third the amplified peak acceleration of the design earthquake. However, at the present time, the authors' opinion is not reflected in official Corps policy.

8. In seismic design and in analyses of new and existing dams, nothing is more critical than the establishment of an accurate, reliable, and representative, even though idealized, soil profile. In design it is required to determine what materials will be left in place and what materials will be removed or treated. Material that is marginally stable must be removed or treated. In the authors' opinion, these are key and critical decisions in the design process. If potentially liquefiable material is left in place, no amount of analysis, no matter how sophisticated, will make the dam safe. Consequently, the time when the designer is establishing the geometry of the dam, the various schemes to be used to control seepage, what foundation materials

will be removed, and what foundation materials will be left in place, is a critical time in the design of a dam. These decisions are some of the most important decisions that are made in the design process and this is the time that critical judgments of "experts" are needed.

9. At this point, it is appropriate to consider the question, "How detailed a soil profile is required?" This question can only be answered on a site-specific basis; however, the profile should be such that it adequately represents the site and that results of response analyses are correct. If, for example, there is a continuous thin seam of soft bentonite underlying the entire site at depth, this seam should certainly be represented as it will act as a shock absorber and to a certain extent isolate the material above it from strong shaking. On the other hand, if the site has interbedded thin seams of sands and clays with similar shear-wave velocities, then their behavior with respect to wave propagation will be similar and a detailed soil layering scheme is not critical for response analysis, though it may be for other purposes. The sometimes critical importance of small geologic details (in a somewhat different context--their effects on seepage) has been pointed out in a classic paper by Terzaghi (1929).

10. It should be always remembered that no analysis, no matter how sophisticated or elaborate, will provide all of the answers. Ultimately, common sense, engineering judgment, and experience are required to design and construct dams in a manner that will protect the public. These components of the engineer's thinking are incorporated in "defensive design" measures which serve (a) to provide protection against hazards that are recognized but cannot be easily analyzed, (b) to mitigate the effects of localized excessive strains, and (c) to provide a second line of defense against damaging actions such as cracking and piping. If an embankment and its foundation are well designed and entirely composed of materials that do not suffer significant cyclic strength degradation, then major dynamic and stability problems are avoided. However, it should not be assumed that such materials will not deform, crack, or slough. Consequently, sound engineering judgment must be used and the principle of designing must be applied to provide defense in depth, long advocated by Professor Arthur Casagrande. For example, dams must be designed so that cracks are not to be expected, but at the same time it must be assumed that cracks may develop and so provide drains and filters to provide a second line of defense against failure by erosion or piping.

11. In summary, if all materials that are susceptible to seismically induced liquefaction have been eliminated, then a well-designed dam for static considerations is, in most cases, safe for dynamic considerations. An example might be where the dam has low freeboard and/or may be subjected to extremely high accelerations.

Analysis of Existing Dams

12. In assessing the seismic stability of an earth dam, the crucial question is "Do the embankment and foundation soils suffer serious loss of shear strength as a result of cyclic loading?" If the answer to this question is yes, then the potential for liquefaction and postearthquake stability must be evaluated. The method used to do this is the analysis of liquefaction or cyclic mobility developed by Professor H. B. Seed and his coworkers (Seed 1979, 1981; Seed, Arango, and Chan 1975; Seed, Lee, and Idriss 1969; and Seed et al. 1973 and 1975) using one- or two-dimensional analyses for dynamic stresses. This analysis is outlined in block diagram form in Figure 1.

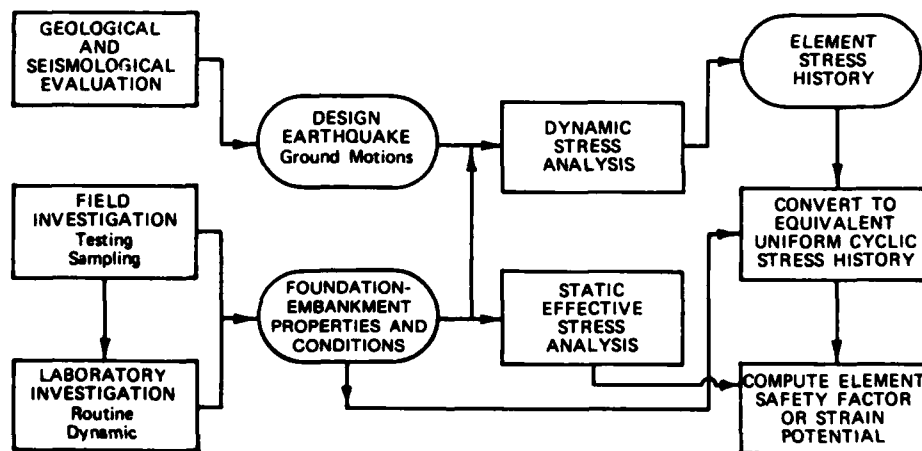


Figure 1. Liquefaction analysis

13. If the answer to the question is no, then liquefaction is not a significant problem and the seismic stability of the dam may be evaluated using the sliding block method of analysis of permanent displacements (Ambraseys and Sarma 1967, Franklin and Chang 1977, Makdisi and Seed 1977, Newmark 1965, and Sarma 1979). Figure 2 shows a diagram of the permanent deformation analysis which is used by WES. This method is based on the

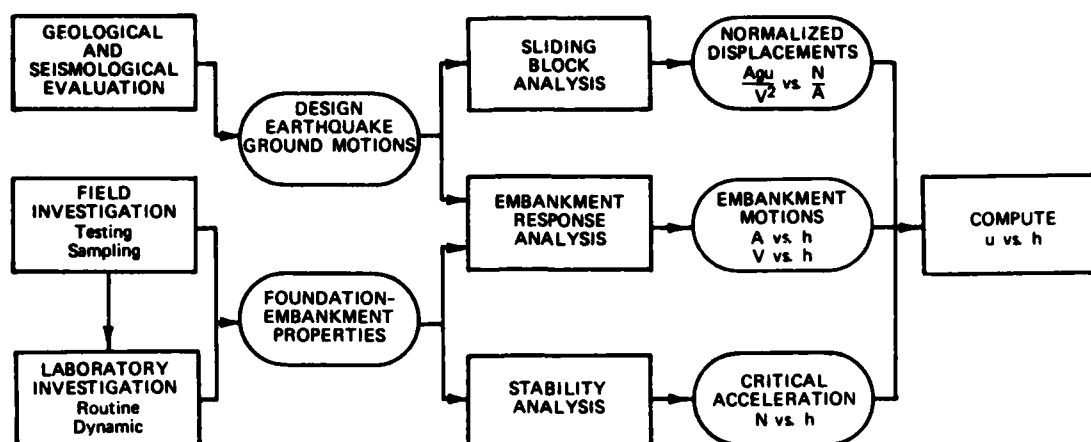


Figure 2. Permanent displacement analysis

concepts outlined by Newmark (1965) and is similar to the analysis method developed by Makdisi and Seed (1977). Permanent deformation analysis should be done if a pseudostatic analysis yields a factor of safety less than 1 for seismic coefficients less than one-third the amplified peak acceleration. In most cases, the relative permanent deformation expected during earthquakes will be small. These two methods of analysis, i.e., liquefaction analysis and the permanent deformation analysis, have been well documented elsewhere. The paper by Marcuson, Hadala, and Franklin (1980) outlines both methods and provides references to more complete descriptions in the literature.

14. The liquefaction analysis described in Figure 1 is based on the use of earthquake-induced stress histories derived from dynamic stress analyses, in conjunction with dynamic soil strengths from consolidated, undrained, stress-controlled, cyclic triaxial tests. The current trend is to put more emphasis on the Standard Penetration Test (SPT) for the evaluation of strength of the in situ material (Seed 1981). An advantage of the SPT approach is that it offers a more representative definition of soil strength than laboratory techniques. Economy dictates that cyclic triaxial tests can be performed only on a relatively small number of undisturbed samples which may or may not be representative of the overall in situ conditions. However, SPT N values may be obtained at numerous and varied locations around the site to obtain a more representative indication of soil strength and its variability.

15. As noted earlier, the seismic evaluation of the existing dam is a much more difficult problem than a seismic design for a new dam, primarily for two reasons: (a) the difficulty in accurately establishing zonation and soil

layers in the profile, particularly in the case of hydraulic-fill dams on alluvial foundations; and (b) the frequent presence of marginally stable materials which would be excluded in prudent design, in the light of today's knowledge. Also the nature of the problem demands that the maximum earthquake for the site be defined much more precisely than is needed in a new seismic design. It will occasionally be found that a seismic stability analysis using an idealized soil profile and embankment zonation will indicate potentially unstable conditions; in such a case, a new subsurface exploration problem arises, that of determining the areal extent of the potentially unstable materials.

16. The seismic analysis of an earth dam is a multidisciplinary problem. It involves input from a seismologist, a geologist, and a geotechnical earthquake engineer. The geologist works in terms of active and inactive faults in the region. The seismologist deals primarily in past seismic events, focal mechanisms, and mechanics of wave propagation. It is the engineer's responsibility to decide what earthquake motion should actually be used in the analysis, and to establish what ultimate factor of safety is to be used. As an example of the importance of this function, Professor N. M. Newmark has pointed out that if each of three participants puts a factor of safety of 1.5 on his input, then the overall factor of safety is 1.5^3 , or 3.375. On the other hand, if each participant puts a factor of safety of 1.1 on his input, then the overall factor of safety on the input is 1.1^3 , or 1.33. One can easily see that it is imperative that compounded conservatism not be allowed.

Mitigating Courses of Action

17. Once a seismic stability problem has been identified, the owner and the engineer are faced with a new set of difficult decisions. On the one hand, considerations of public safety do not allow the continuing existence of a potentially unstable and dangerous situation. On the other hand, any remedial work is bound to be expensive, and the profession has little experience with remedial work of this kind for guidance. Among the difficulties and adverse impacts the engineer will have to deal with are those of verification: he must be able to verify that the work achieves the intended result, and he must demonstrate that its effects are in the right direction--that it positively improves stability. Thus, verifiability will be an important consideration in

determining the best course of action in a particular case.

18. While the Corps of Engineers, in particular, has not yet had to face this problem, the ongoing program of seismic evaluation of existing dams may lead to the discovery of some for which state-of-the-art techniques cannot guarantee the seismic stability. In that case, a decision must be made on what remedial measures or other courses of action are required. This obviously will be a very difficult decision and one that will be made at the highest levels within the organization, though it will require a great deal of technical assistance and advice from the technical staff. Because each dam and each dam site is unique, there will never be a routine approach to seismic stabilization treatment for earth dams, but preliminary study of the problem suggests that there will be a fairly limited number of approaches from which to choose. The one that is most appropriate for a particular case will depend on the precise nature of the threat to stability, the overall conditions of the dam, and the consequences of failure. In the following paragraphs, courses of action that have been identified as being potentially feasible are discussed, depending on the specific case or site conditions.

No action

19. In some cases it may be concluded that the probability and consequences of failure are sufficiently small that the risk is a tolerable one; then no remedial action would be necessary. The reasoning behind such a course of action follows from the fact that major earthquakes are, in general, rare events. Maximum earthquakes with return periods of 100's to 10,000's of years are presently being used. If the dam can be shown to be safe for lesser earthquakes with shorter return periods, then the risk might be acceptable, especially if only economic loss is involved. Certainly, some level of risk must be acceptable, since there is no such thing as "zero risk." Risk is knowingly accepted every day, though individuals generally have something personal to gain by doing so. Additionally, the hydraulic design of a dam admits some probability of overtopping failure for floods larger than the "probable maximum flood." Return periods of probable maximum floods are believed to be 200 to 500 years. One can argue that the risk of failure due to an earthquake does not need to be smaller than the risk of overtopping failure, but one must ask that the level of risk be in balance with the public interest in the areas of safety, economics, and sociology. Ultimately, a decision on what constitutes an acceptable level of risk is one of public

policy, and is not a proper exercise of engineering judgment. Negative factors in the "no action" option include the following:

- a. Engineers will have many problems in presenting the risk-based analysis and design to the public, primarily because of lack of experience.
- b. The data base on return periods of earthquakes is weak.
- c. Presently, only judgments can be made about the combined probability of experiencing the design earthquake and probability that the dam will fail if it occurs.
- d. If a large flood is forecast a few days ahead of time, additional precautions can be taken. Currently, earthquakes cannot be forecasted.

Regulation of public access downstream

20. Damage to private property and/or loss of life could be prevented by purchasing or regulating access to and use of downstream land that would be flooded as a result of the failure of the dam. Such an approach is technically feasible because the extent of the flooded region resulting from sudden breaching of the dam with a full reservoir can be calculated with reasonable accuracy. The Corps of Engineers and other agencies have considerable field experience with such predictions through routine floodplain management practices. Such an approach might be viable for many rural areas, especially if the reservoir is small, but would not be practical for political and/or cost reasons in urban areas where the cost of land is high. It suffers the further disadvantage that some loss of life could occur in the event that some users or trespassers on the property failed to be warned of impending danger.

Partial lowering of pool

21. This solution increases the effective stresses and provides greater freeboard to retain the pool in the event of a stability problem. Additionally, it reduces the downstream flood in the case of dam failure. A precedent is Jackson Lake, Wyoming, where U. S. Bureau of Reclamation engineers (Von Thun 1978) recommended this action as an interim solution for a dam tentatively judged to be seismically unstable. This solution reduces the potential flood to a point where possible damage is tolerable. Such a course of action can be easily verified, and it definitely improves stability and reduces the consequences of failure. Negative factors, arising from the partial loss of function, are that it potentially could have a major regional social and economic impact, depending on the reservoir usage, and may not be suitable for navigation or recreation pools.

Permanent emptying of the reservoir

22. Such a recommendation would satisfy the safety criteria of ER 1110-2-1806. It would not be without precedent, since the Corps as well as other Government agencies have been involved in inspections which have led to decisions to breach privately owned dams. This decision would be relatively easy to reach for small dams of little importance, and it is 100 percent sure and easily verified. It has the disadvantage that whatever benefits and protections derive from the dam, such as flood control, power generation, and recreation, would be lost.

In situ densification of the foundation

23. Experience indicates that vibroflotation or the use of compaction piles with soil replacement can increase the relative density of foundation sands to about 70 percent. In most cases such an improvement would be adequate to preclude flow failures, but present knowledge suggests that large strains are still possible in the event of large earthquakes. Such techniques have been used to densify sands prior to construction but have not yet been used under an existing dam. Under favorable conditions, such an approach would have the advantage of moderate cost as compared to some other methods, and the increase of density can be approximately verified using cone penetrometer tests, SPT, fixed-piston undisturbed samples, and measurements of surface heave and displacement. On the other hand, problems of differential settlements of the embankment and the development of preferential seepage paths with a potential for piping could result. In fact, differential settlements would be unavoidable and the potential for cracking and piping would be relatively high. Other problems might result from damage to locks or other adjacent concrete sections and in an extremely unstable foundation, the vibrations due to this activity could possibly trigger a flow failure. Also, remolding of the sands by the densification process would mean that the gain in strength due to densification would be partially offset by the loss of the beneficial effects of age on the sand structure.

Surcharge

24. In many instances stability can be improved by the use of berms and/or increasing the height of the embankment, which will result in higher effective confining pressures in the embankment materials and the foundation. This increase in initial effective stress increases the dynamic strength and the shear modulus of cohesionless soils. Additionally, the greater height will

produce a greater freeboard, which is a partial protection against reservoir loss in the case of stability problems. Verification of such action is straightforward since it relies only on measurements of geometry. One can also be 100 percent confident that the effect of increases in effective stress will be to improve the liquefaction resistance of cohesionless materials. On the other hand, preliminary analysis of the increase in liquefaction resistance reveals that modest surcharges will produce modest improvements in strength, so that impracticably high berms or additions to the dam would be required in some cases depending on the depth of the soil in question. Verification of the ultimate safety of the dam requires reliance on the definition of the design earthquake, on the accurate measurement of liquefaction resistance from laboratory tests or SPT, and on the accurate prediction of dynamic stresses from a dynamic analysis. A further uncertainty is that in the event of a flow slide, the amount of effective freeboard remaining would be very difficult to predict.

Dewatering

25. A potential solution is the permanent dewatering of saturated liquefiable zones. This would increase the effective stress, strength, and moduli, all of which are effects beneficial to stability. Also, partially saturated materials are not susceptible to seismically induced liquefaction. While there is a case on record of seismically induced "liquefaction" of dry loess (Terzaghi 1950), its initial state must have been much looser than anything allowed in a dam foundation. Also, capillary tension in a wet, but unsaturated cohesionless soil would make it more resistant to liquefaction than a dry soil. Positive factors include the facts that the liquefaction threat is eliminated even if the dewatering system does not survive the earthquake, and that if dewatering is successful, it is 100 percent effective and it can be easily verified by piezometers. However, dewatering a foundation sand below the water table is easier said than done. It might require continuous pumping as well as upstream and downstream slurry trenches, and even then there is no guarantee at the outset that one can in fact dewater an alluvial foundation.

Reduction in drainage paths

26. Stone columns or relief wells could be installed to reduce the lengths of drainage paths, thus allowing draining to occur during the earthquake. Limited drainage greatly reduces pore pressure buildup during cyclic loading. Stone columns have been installed at the Jensen filtration plant

following the San Fernando earthquake (Seed and Booker 1976). The effectiveness of the stone columns or relief wells could be verified with field pumping tests and piezometers. On the negative side, there is no proven way to install graded filters around stone columns and consequently, no way to eliminate the possibility of piping. It cannot be guaranteed that these drains will not clog with time. No available field testing method exists to verify the performance of this action short of the actual earthquake occurrence.

Grouting

27. The use of chemical and/or cement grout will increase the strength and stiffness of the foundation. Also, chemical and cement grouts are commonly used to reduce groundwater flow because they reduce average permeability. The increase in strengths in zones where the grout has penetrated can be verified by undisturbed sampling and testing. The decrease in permeability increases the drainage time and could increase the chance of postearthquake instability problems. Grouting is extremely expensive, and it is difficult to predict where the grout will go. Grouts do not effectively penetrate silts and fine sands, so it cannot be guaranteed that continuous zones of liquefiable material will not remain even after a diligently executed grouting program. Additionally, there is a toxicity problem with some grouting chemicals; environmental considerations would preclude their use.

Construction of a replacement structure

28. A new structure can be designed to resist almost any earthquake shaking, based on the current state of knowledge. The authors believe this solution to be virtually 100 percent sure except in the epicentral regions of magnitude 8.0 plus earthquakes. The density of all the materials in the structure and foundation can be verified. An additional positive factor is that in some cases one can take advantage of the same spillway or diversion channel used in the original project. On the negative side, this solution is very expensive, requires a new environmental impact statement, and deprives the region of the benefits of the reservoir for a period of years. Such an action would have a high degree of visibility, and it is likely that the public reaction would be strong and negative.

Replacement in a new location

29. An extreme solution to the problem of a potentially unstable dam would be to build a replacement structure some distance upstream or downstream and then to breach the old structure. Such a solution would be virtually

100 percent safe except in the epicentral region of magnitude 8.0 plus earthquakes because a new structure can be designed to resist almost any earthquake shaking. If cost is not a factor, then all doubtful materials can be removed from the foundation and dense rolled-filled earth can be used for backfill, or a rock-fill design can be used. Also, defensive design measures can be incorporated from the outset. Such a solution offers the problem of high expense, the requirement of a new environmental impact statement, and that in some cases an acceptable site for the replacement dam may not exist.

Construction of a detention dam

30. A secondary dam, built at a suitable location downstream, could either store or control the floodwater in the event of a failure of the main dam. Such a solution is within the current state of the art and was in fact used as a secondary line of defense when Los Angeles Dam was built to replace the Lower San Fernando Dam. This option has many of the same advantages and disadvantages as replacement in a new (downstream) location. Two additional advantages are that the cost should be lower because it would be dry until the main dam failed, and it would permit limited use of the land between the dams.

31. All of the proposals discussed above are considered to be feasible, though each one has its own advantages, disadvantages, and relevance to particular structures or sites. Obviously, many combinations of these approaches would also be feasible. A few other ideas have been considered but rejected as probably not feasible. They include such suggestions as desaturation of the foundation materials by injection of air. Such schemes were rejected primarily because of lack of experience in designing and constructing them and because their reliability is considered doubtful.

Summary

32. In this report current methods for seismic design and analysis of new and existing earth dams have been discussed. The point has been made that in general the design of a new dam is easier than the analysis of an existing dam. This is due largely to the difference between specifying the materials and zoning to be used (design) and determining, sometimes long after the fact and with incomplete records, what the actual as-built conditions are. Also, in a new design marginal materials, which are troublesome to evaluate, can always be omitted.

33. Additionally, possible courses of action for treatment of foundations and existing dams that are judged to be susceptible to earthquake-induced failure have been discussed. In general, these methods are expensive and some would have adverse environmental, social, or economic impacts. It must be emphasized that it is extremely important that the accomplishment and the effects of the proposed remedial work be verifiable.

34. Little field experience has been obtained to serve as a guide in dealing with the treatment of dams that have potential seismic stability problems. Consequently, as this problem is dealt with in the 1980's, emphasis must be placed on diligently collecting and fully using whatever relevant experience is available.

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